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Challenges and Opportunities for Organic Hop Production in the United States

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Review & Interpretation

ABSTRACT

Hop cones grown on the female plant of the perennial crop (*Humulus lupulus* L.) are an integral component of the brewing process and provide flavor, bitterness, aroma, and antimicrobial properties to beer. Demand for organically grown hops from consumers via the brewing industry is on the rise; however, due to high N requirements and severe disease, weed, and arthropod pressures, hops are an extremely difficult crop to grow organically. Currently, the majority of the world's organic hops are grown in New Zealand, while other countries, including China, are beginning to increase organic hop production. Land under organic hop production in Washington State, where 75% of the hops in the United States are grown, increased from 1.6 ha to more than 26 ha from 2004 to 2010, and other hop-producing states demonstrate a similar trend. Removing hops from the USDA Organic Exemption list in January 2013 is expected to greatly increase organic hop demand and will require corresponding increases in organic hop hectarage. Current challenges, including weed management, fertility and irrigation management, insect and disease pressures, and novel practices that address these issues will be presented. Here, we discuss current and future research that will potentially impact organic hop production in the United States.

The first use of hops—with the tender shoots and young leaves used as a salad (Burgess, 1964)—was described in the first century A.D. in Pliny's *Natural History*. The earliest records of hop cultivation date back to the 8th century, when French and German monks grew hops, presumably for their medicinal value (Burgess, 1964). Hops have a long history of use for medicinal purposes, and they have most often been used as a mild sedative due to their anti-anxiety properties. It was not until the 12th century that hops became widely used as a preservative and clarifying component in the beer-brewing process (Burgess, 1964). Hop cultivation and brewing have been an important part of American culture since the first colonists arrived. By the mid-1600s, widespread cultivation of hops was becoming commonplace, with farms up to 18 ha in size. Hop production had spread from New York to Wisconsin, and finally to the Washington Territory and California by the late 1800s (Steiner, 1973).

The *Humulus* genus is made up of dioecious (rarely monoecious), perennial, short-day flowering plants of the family Cannabaceae and is indigenous to northern temperate climates (Mahaffee and Pethybridge, 2009; Small, 1978). The *Humulus* genus has three distinct species: *H. japonicas* Siebold & Zucc., *H. yunnanensis* Hu, and *H. lupulus* L. *Humulus japonicas* is an annual species native to China, Japan, and Taiwan and is cultivated primarily for its ornamental value. It has been introduced to Europe and North America and is now considered a semi-invasive species in some areas of the eastern United States (Mahaffee and Pethybridge, 2009). *Humulus yunnanensis* is a relatively unknown species thought to have originated at high elevations in the Yunnan province of southern China (Mahaffee and Pethybridge, 2009). *Humulus yunnanensis* is not widely cultivated, and, according to Small (1978), is often confused with *H. lupulus*, while other, more recent sources report that it is a rare species (Mahaffee and Pethybridge, 2009). *Humulus yunnanensis* is not found in the USDA's national plant germplasm system (Mahaffee and Pethybridge, 2009).

Humulus lupulus, widely known as the common hop plant, is the species that possesses marketable traits used for brewing. It consists of a number of taxonomic varieties: *H. lupulus* var. *neomexicanus* A. Nelson & Cockerell adapted to western cordilleran conditions; *H. lupulus* var. *cordifolius* (Miguel) Maximowicz distributed in eastern Asia, most notably Japan; *H. lupulus* var. *pubescens* E. Small of the Midwestern United States; *H. lupulus* var. *lupuloides* E. Small of eastern and central North America; and *H. lupulus* var. *lupulus,* which originated in Europe but has spread to Asia, Africa, and eastern North America and is the taxonomic variety responsible for retaining most of the favorable brewing characteristics (Hampton et al., 2001; Mahaffee and Pethybridge, 2009). One other taxonomic variety, *H. lupulus* var. *fengxianensis* J.Q. Fu, has also been described (Peredo et al., 2009). Overlapping and introgression is evident for some varieties (Mahaffee and Pethybridge, 2009). Though wild hops cannot be used directly for brewing due to

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Abbreviations: AOHGA, American Organic Hop Grower Association; NOSB, National Organic Standards Board.

Fig. 1. Young hop bines in an organic hopyard, springtime in Washington's Yakima Valley.

unfavorable chemical characteristics, germplasm from wild *H. lupulus* var. *lupuloides* has been used to create successful cultivars, including 'Brewer's Gold', 'Bullion', and 'Northern Brewer'. Wild germplasm sources offer many genetic attributes that are beneficial in breeding operations, including biological resistance to disease and pests (Hampton et al., 2001).

Hops are most often commercially propagated by cuttings of a female plant, producing clones of the parent variety. Hopyards are generally replanted when market demands or reduced yields necessitate replacement (Fig. 1). Replanting every 10 to 20 yr or less is common, although the plants can produce for much longer (Beatson et al., 2009). Hops can be grown in a wide variety of climates, including semiarid, maritime, humid continental, and sub-tropical regions, with different cultivars being more adapted to different climatic conditions. Generally, hop production is limited to regions above 35° N or S lat (Mahaffee and Pethybridge, 2009). A dormant period with 5 to 6 wk of near-freezing temperatures is required for optimal growth, and hop crowns are able to survive temperatures of –25°C or lower when insulated by snow or soil (Beatson et al., 2009). Ideal soil types vary considerably, but all should be deep and well-drained to promote optimal growth of the large root mass of the hop plant (Burgess, 1964). The perennial root system of a well-developed hop plant can grow more than 4 m deep and up to 5 m laterally (Beatson et al., 2009; Burgess, 1964). This extensive root system is necessary for uptake and storage of the water and nutrients necessary to facilitate rapid growth in the spring and summer months (Beatson et al., 2009; Burgess, 1964).

Germany is the world's leading hop-growing country, producing approximately 42,000 of the 151,850 Mg produced globally in 2009 (FAO, 2010). The United States is currently the second-leading hop-producing country, with 36,280 Mg of hops harvested in 2008 and more than 42,000 Mg in 2009, valued at more than US$336 million (USDA, 2010). In 2010, approximately 12,660 ha of hops were harvested in the United States. Typical yields vary greatly between cultivar, but yields of 1500 to 2000 kg ha^{-1} are common (George, 2011). Within the United States, hop production is concentrated in the Pacific Northwest, with about 80% of hops grown in the Yakima Valley of Washington, 13% grown in Oregon, and approximately 7% grown throughout Idaho in 2010 (USDA, 2010).

ORGANIC HOPS

A New Challenge

Organic hop production currently makes up a small but steadily increasing percentage of the worldwide hop supply. Certified organic hop land increased from 1.6 ha to more than 26 ha in Washington State from 2004 to 2010, with another nearly 7 ha in transition in 2010 (Kirby and Granatstein, 2011). Fledgling organic hop production industries also have taken root in states such as Michigan, New York, and Vermont, totaling approximately 10 ha of certified organic hopyards throughout the Northeast and 25 ha in Michigan in 2011 (H. Darby, personal communication, 2011). In Oregon, certified hops are grown on 9.3 ha in 2009 (Kirby and Granatstein, 2010). A recent report by the American Organic Hop Grower Association reports that 51 ha of U.S. hops were certified organic in 2010 and 146 ha and at least 18 cultivars will be certified for the 2012 harvest (American Organic Hop Grower Association, 2011). Much of the current organic hop production is taking place in New Zealand, while China is also starting to grow organic hops (Keupper et al., 2005). Organic beer and wine, although comprising only a 0.6% share of the organic market in 2003, increased at an average rate of 10.9% annually during the 5-yr period from 1998 to 2003 (Lotter, 2003).

Organic production has been hampered since June 2007, when hops were added to the National List of Allowed and Prohibited Substances by the USDA's National Organic Standards Board (NOSB)—a ruling that allowed certified organic beer to be brewed with non-organic hops (USDA, 2007). At the time, the supply of organic hops was insufficient to meet the demand of organic brewers. Consequently, some organically grown hops found no buyer, and growers stored their harvests instead of selling them for a loss at non-organic prices.

The situation began to change in December 2009 when the AOHGA petitioned the NOSB to remove hops from the National List, arguing that supply had become sufficient to meet demand and that organic hectarage could be further expanded to grow additional cultivars for organic brewers. In September 2010, however, the NOSB's Handling Committee rejected the growers' petition and recommended that hops remain on the National List. In response, the AOHGA spearheaded a campaign to bring public pressure on the Handling Committee to reconsider its recommendation. A detailed blog post on a grower's website eventually generated more than 6000 hits, fueled by links from a popular beer blog, social media, and the electronic newsletter of a major organic consumers association, among other Internet communication. E-mail chains radiated outward from growers, brewers, organic activists, and scientists involved with sustainable hop production. Newspapers in at least three states ran stories, op-eds, and letters to the editor on the issue. Nearly 150 public comments were recorded on the USDA website before the NOSB met in Madison, WI, in late October 2010—nearly all of them advocating that hops be removed from the list. As a result, the Handling Committee reversed course and recommended the sun-setting of the hops exemption, which the full NOSB voted to adopt. Beginning 1 Jan. 2013, brewers must use organic hops in all USDA-certified organic beer

(NOSB, 2010). Growers and brewers expect a significant increase in demand for organic hops as a result of the ruling, and considerable growth is expected in the organic hops industry to meet the new requirement. Organic hop research will need to expand to assist farmers in their efforts to establish effective agronomic practices for growing organic hops in the United States.

Obstacles and Opportunities

Organic hop production is a small but growing industry that faces many agronomic challenges. Hops, being a clonally reproduced, perennial crop that is grown across entire fields for multiple years, results in extremely high volumes of genetically identical material. The genetic uniformity present in perennial monocultures encourages susceptibility to diseases and pests (Darby, 2004). Though brewing demands do not require that hops be grown in monoculture, growers must keep the cultivars separate throughout harvest and processing. Organic production may need to employ new tactics, such as planting different cultivars in close proximity to one another, which often reduces pest and disease pressure (Mundt, 2002; Zhu et al., 2000). However, mixed or strip cropping in hopyards will require more complex management strategies.

Most pests and diseases of the hop plant have a direct influence on profitability of the crop through loss of yield or quality (Gent, 2009). Disease, fungal infection, and arthropod pests that can damage hop cone quality are controlled by frequent and persistent application of pesticides in conventional hopyards, an option unavailable to organic hop growers (Darby, 2004; Gent, 2009). Hop quality is not only a measure of its acid content and brewing characteristics but also its storability, look, feel, smell, and general aesthetics of the final product (Darby, 2004). Due to the direct correlation between quality and price of hops, a crop can be drastically affected by pests and diseases that alter not just the brewing quality but also the aesthetics of the crop as well. Any loss of quality can cause a crop to lose value or be damaged to the point at which it is completely unsalable.

Nitrogen

The perennial crown of the hop plant produces large, annual, twining bines that can reach heights of 7 m or more (Fig. 2) (Hampton et al., 2001; Mahaffee and Pethybridge, 2009). The bines or shoots of the plant climb in a clockwise direction with the aid of small, stout, hooked hairs (trichomes), as opposed to vines, which climb with the aid of tendrils (Mahaffee and Pethybridge, 2009; Probasco, 1997). Though little N is absorbed (about 10%) before mid-June, by the end of July, hops have generally taken up the majority of the annual N, between 90 and 180 kg N ha^{-1} (Sullivan et al., 1999). Hop bines emerge in early spring and can grow rapidly, up to 25 cm d^{-1}. Hops can consume up to 4.5 kg N ha^{-1} d^{-1} during periods of rapid bine growth (mid-June in the Pacific Northwest), and high levels of N should be available before this period begins (Sullivan et al., 1999). After the summer solstice, the plant reacts to the decreasing day length by beginning the flowering process, during which the inflorescence (cones) is (are) formed (Mahaffee and Pethybridge, 2009). After harvest, the discarded material (bines and leaves) can be returned to the hopyard to supplement future fertilizer input, but it should be composted to reduce the likelihood that viable pathogens remain in the residue (Gingrich et al., 1994; Mahaffee and Pethybridge, 2009; Noble and Roberts, 2004).

Fig. 2. Organic hopyard, late July in the Yakima Valley.

Hop harvest in the United States typically occurs from mid-August through late September, depending on the cultivar (Beatson et al., 2009). On average, 112 to 168 kg N ha^{-1} is taken from hop fields annually, but the amount is dependent on many factors, including yield, age, soil characteristics, and cultivar (Gingrich et al., 1994). Studies in southwestern Washington showed that the dry cones make up 28% of the total aboveground dry matter and approximately 32% total aboveground N (Hermanson et al., 2000). A similar study in the Willamette Valley of Oregon showed that higher levels of N (about 42%) were removed via cones during harvest (Hermanson et al., 2000). In southeastern Washington, N removed from the field in the cones during harvest averaged 51 kg ha^{-1}, and cone N content was not largely dependent on N application rates, which were tested from 0 to more than 240 kg N ha^{-1}. This independence from the N application rate is likely due to the high amounts of residual N in the soil in the years tested (Hermanson et al., 2000).

It can be difficult to meet crop N demands in organic systems (Pang and Letey, 2000). Cost-effective organic fertility strategies will need to be developed to meet the high N requirement of hops. The implementation of leguminous cover crops and their soil-stabilizing, soil-building, and N_2-fixing abilities provide economic advantages. A review by Hartwig and Ammon (2002) demonstrated that, in the long term, N_2-fixing cover crops more than pay for seeding costs by reducing the need for other N inputs. Leguminous cover crops can contribute substantial amounts of N and may be able to supplement a significant portion of the N needed for hop plants. In a recent vineyard study, Ovalle et al. (2010) found the N contribution in aboveground biomass by leguminous cover crops to average 112 to 161 kg N ha^{-1} yr^{-1}. They estimated the total N contribution to be higher, as up to 40 to 50% of additional N in a legume crop may be below ground and associated with rhizodeposition of N and the N contained in nodulated roots. However, the challenge of using cover crops to supply N will be the timing of mineralization and release of N from cover crop residue during crucial uptake periods. Sirrine et al. (2008), working in Michigan cherry orchards, also found that groundcover management systems that included leguminous cover crops and one-half rate N fertilizer were an economically viable alternative to conventional groundcover management. Additionally, crop losses during low-harvest years due to severe weather can be minimized by using cover crops because of the reduced input costs of N (Hartwig and Ammon, 2002).

Although compost and manure amendments are used as fertility sources in conventional hopyards, these fertility sources will most likely play an even more significant role in supplying nutrients to organic hops. Maintaining a diverse crop rotation that includes green manures is a common means of N management in organic cropping systems (Watson et al., 2002). Livestock-based manure and composts have been shown not only to supply essential nutrients to crops but also to increase physical and biological properties of soil (Darby et al., 2006). A review article by Stone et al. (2004) highlighted that partially composted plant and livestock-based soil amendments can also suppress many soilborne and foliar pathogens. Organic hop production systems will certainly require a combination of strategies to supply necessary nutrients to the crop and promote disease control.

Nitrate levels are often found to be higher in conventional vs. organically grown products (Hengel and Shibamoto, 2002; Lotter, 2003), however, specific information comparing organic and conventional hop nitrate levels is lacking. While hop cone nitrate levels do not have a direct effect on brewing quality, consumers have been concerned about nitrate levels in food (Hord et al., 2009). Results showed nitrate levels in fertilized hops were significantly higher than those of unfertilized hops in a comparison of hop cones from plants of 'Aurora' and 'Savinjski Golding', which were fertilized from 0 to 600 kg ha^{-1} N (Majer and Virant, 2003). Nitrate content was as high as 1460 mg 100 g^{-1} dried cones in fertilized Aurora, whereas nonfertilized dry cones ranged from 76 to 491 mg 100 g^{-1}. Nitrates transferring to wort (unfermented beer, which contains constituents of malt, water, and hops) were higher when using fertilized hops, but the result was not as significant as the difference of N rates in cones (Majer and Virant, 2003). However, due to the high N inputs required by the hop plant, nitrate levels in organic hop cones are likely to be higher than those of unfertilized cones.

Weeds

Weeds are considered one of the most difficult obstacles to overcome in successful organic production systems (Bàrberi, 2002), and hops are no exception. Hops require a large amount of water and nutrients during periods of intensive growth, and weeds can affect nutrient and water uptake (Lipecki and Berbeć, 1997). The accepted method of weed control in most conventional hopyards involves mechanical tillage of the drive-rows with herbicide applications in-row (Lipecki and Berbeć, 1997). However, conventional weed management and cultivation strategies vary significantly depending on the growing region and the specific needs of the particular hopyard. Practices may include disking, harrowing, subsoiling, cover-cropping, mowing, and herbicide application (Beatson et al., 2009; Lipecki and Berbeć, 1997; Parker, 2009).

Historically in Washington hopyards, cultivation has been the primary method of weed control, and it can lead to problems with water quality, soil health, N retention, and disease (Beatson et al., 2009; Steenwerth and Belina, 2008). Other problems—such as increasing nutrient mineralization, bringing weed seeds to the surface, stimulating growth of some weeds, and exacerbating the presence of Verticillium wilt through physical wounding and dissemination of infected material—can be caused by intense cultivation. Thus, cultivation and physical controls are often ineffective as an exclusive method of weed control, though cultivation is valuable for incorporating organic matter into the soil and increasing nutrient availability (Bàrberi, 2002; Beatson et al., 2009). Some reports suggest that subsoiling (deep plowing) can increase yield in hopyards by improving soil characteristics, reducing compaction, increasing available nutrients, and reducing the presence of fungi of the genus *Verticillium* and *Fusarium* (Lipecki and Berbeć, 1997).

In some instances, cultivation is foregone to help establish cover crops in the drive-rows to attract beneficial insects, help stabilize the soil, and enable machinery to drive in the yard sooner after precipitation. Cover-cropping may be an important tool for controlling weeds in organic hopyards (Hartwig and Ammon, 2002). The benefits of incorporating cover crops into agricultural systems are well-known. They include improvements in soil health, pest suppression, water retention, and N retention, making cover-cropping an important tool in production of organic crops (Abawi and Widmer, 2000; Grasswitz and James, 2009; Ramos et al., 2010; Thorup-Kristensen et al., 2003). Cover crop use has become an invaluable tool in soil building and pest management in organic orchards, and thus will likely have implications in organic production of many perennial crops (Fernández et al., 2008).

A drive-row cover crop of rye (*Secale cereale* L.) that is annually plowed under has been used to combat weeds and add organic matter to benefit the soil (Lipecki and Berbeć, 1997). Cover crop mulching has shown promise in controlling weeds in vineyard systems and may prove useful in hopyards as well (Steinmaus et al., 2008). Similarly, the use of a roller-crimper for termination of fall-planted cereals may work well in organic hopyards (Ashford and Reeves, 2003). In most cases, weed densities are reduced by the presence of cover crop residue, except for certain species that do not respond negatively to the smothering effect and reduced light levels caused by the residues (Teasdale et al., 1991). Fall- or winter-planted cover crops offer advantages as well, because they can be mowed or rolled in spring and used as mulch, both preventing weed emergence and reducing competition from cover crops for water and nutrients. Additionally, certain cover crops have been shown to reduce weed biomass and suppress weed germination after incorporation (Kumar et al., 2009). Research in vineyards shows that weed management can be highly variable depending on environmental and agronomic practices (Sanguankeo et al., 2009). This environmental and cultural variability in weed suppression is present in most crop systems including those of hops (Sanguankeo et al., 2009). While cover-cropping tactics likely will have benefits in controlling weeds in organic hopyards, research is needed to determine the effectiveness of specific treatments. Effective weed-control programs in organic hopyards likely will consist of a combination of cultivation and tillage practices combined with the use of cover crops.

Diseases

Major fungal diseases impacting the hop plant include: downy mildew, caused by *Pseudoperonospora humuli* (Miyabe & Takah.) G. W. Wilson; powdery mildew, caused by *Podosphaera macularis* (formerly called *Sphaerotheca humuli*)—although several other species are suspected, though not proven, to cause powdery mildew in hops; and verticillum wilt caused by several species in the genus *Verticillium* (Johnson et al., 2009; Mahaffee et al., 2009b; Radišek, 2009; Seigner et al., 2005). These three diseases represent some of the largest threats to crop yield and quality.

Powdery and downy mildew both can have significant negative effects. Powdery mildew can severely reduce yield and quality. Since its accidental introduction to the United States in 1996, U.S. growers have had to spend up to \$740 ha^{-1} to combat powdery mildew on susceptible cultivars (Elstein, 2002; Mahaffee et al., 2009b). In 2002, German hop growers spent approximately US\$7 million in fungicides to combat this disease (Seigner et al., 2005). Powdery mildew has not been detected in hopyards in Australia, New Zealand, or South Africa, giving these countries an advantage in production. Strict quarantine efforts are present to prevent its introduction (Johnson et al., 2009; Mahaffee et al., 2009b). Downy mildew has had devastating consequences for hop cultivation in the humid regions of the eastern United States, as well as in western Washington and Oregon, among other humid regions where the disease flourishes. Resistance to downy and powdery mildews is of great importance to growers. However, the volatile and changing market does not always allow for production of resistant varieties. Resistance genes often are found in wild hop samples, which will provide useful and resistant parent material for organic breeding efforts (Seigner et al., 2005; USDA, 2007). Cultivars resistant to downy mildew include: 'Cascade', 'Fuggle', 'Perle', 'Tettnanger', and 'Willamette', among others (Johnson et al., 2009). In addition to resistance, other traditional means to control downy and powdery mildew include a combination of cultural practices and timely fungicide applications. Cultural practices include removal of infected material, sanitation, timely pruning and removal of basal growth, and water and fertility management (Gent et al., 2009).

Other notable hop diseases caused by fungi and oomycetes include alternaria cone disorder (*Alternaria alternata*), armillaria root rot (*Armillaria mellea*), ascochyta leaf spot primarily caused by *Ascochyta humuli*, black root rot (*Phytophthora citricola* Sawada), cone tip blight (several *Fusarium* species), gray mold (*Botrytis cinerea*), red crown rot caused by a species of *Phacidiopycnis*, sclerotinia wilt [*Sclerotinia sclerotiorum* (Lib.) de Bary], septoria leaf spot caused by several species of *Septoria humuli*, and sooty mold that is expected to be caused by various *Cladosporium* species (Mahaffee et al., 2009a).

Several virus and viroid-caused diseases are of increasing concern to hop growers, and their effects vary with cultivar and viral strain (Pethybridge et al., 2002). Hop latent virus, American hop latent virus, and hop mosaic virus, each of the genus *Carlavirus*, are primarily transmitted through mechanical means or by the damson-hop aphid (*Phorodon humuli* Schrank). Symptoms of infection are not often prominent, but chlorosis of the leaves is common. Influences of these viruses on hop yield and quality is largely dependent on sensitivity of the cultivar (Eastwell et al., 2009). Other important viruses that negatively impact hop production include apple mosaic virus and arabis mosaic virus, both of which cause reduced vigor, quality, and yield and are highly dependent on cultivar and location (Pethybridge et al., 2008). Most viruses tend to cause increased mortality during propagation. Environmental and cultural influences interact with viruses in a multitude of different ways, and their effects on yield and growth are thus highly variable between cultivar, viral strain, country, and environment (Pethybridge et al., 2002; Pethybridge et al., 2008).

Hop stunt disease is caused by the Hop stunt viroid, which originated in Japan. It causes shortened internodes on the bines and reduced plant height, vigor, yield, and quality (Eastwell and Sano, 2009; Pethybridge et al., 2008). Hop latent viroid is found in hopyards worldwide, is mechanically transmitted, and thus is thought to be largely ubiquitous. Effects of the viroid vary greatly with regard to yield and quality reduction (Pethybridge et al., 2009). In most cases, virus- and viroid-infected hops will be removed when the loss from reduced quality and yield outweighs the cost of replanting.

Disease prevention in organic hopyards will rely heavily on breeding efforts that focus on disease resistance, as well as careful screening efforts. Reducing the extent to which a monoculture is present in the organic hopyard by alternating varieties planted would likely reduce the rate of infection but would also increase labor costs (Darby, 2004). Organic control of diseases will need to involve a combination of approaches to keep levels low: proper hopyard design, good sanitation, resistant or tolerant varieties, forecasting, other cultural practices, and the use of organically approved fungicidal products. Research and development of biological controls and resistant varieties would greatly increase the success of organic hop production. Current efficacy of approved organic bio-controls registered for hops should be determined.

Arthropod Pests

Key pests of the hop plant include the two-spotted spider mite (*Tetranychus urticae* Koch), an important pest worldwide, and the damson-hop aphid, which is most notable in the hop-growing regions of the northern hemisphere (Grasswitz and James, 2009). The two-spotted spider mite is a widespread and common pest that can significantly reduce cone yield and quality. These mites thrive under hot, dry, and dusty conditions, and they produce webbing, which helps to protect them from predators, as well as chemical sprays (Fig. 3).

The two-spotted spider mite and damson-hop aphid historically have been controlled with broad-spectrum insecticides. Recently, with the use of selective insecticides to control these pests and efforts to preserve beneficial insect populations, other minor pests have increased in significance. Currently the two-spotted spider mite and hop aphid represent the most problematic species to organic hopyard management (Grasswitz and James, 2009). The hop aphid exists in many parts of the northern hemisphere and can devastate hop plants, its summer host. The biggest threat that aphids pose to hop production is their tendency to feed on hop cones late in the season, which greatly reduces quality, increases the presence of sooty mold, and may be responsible for the transmission of some hop viruses (James and Barbour, 2009). Aphids and mites can be reduced to some degree through the use of beneficial insects, which include various lady beetles and predatory mites, as well as a wide variety of other predatory insects (Gent, 2009; Weihrauch, 2009). Beneficial insects can be attracted to the hopyard through the addition of flowering plants and the increased ground litter present with the addition of cover crops to the hopyard (Grasswitz and James, 2009).

Integrated management strategies to control mite populations include cover-cropping to increase beneficial predator insect

Fig. 3. Hop plant severely damaged by two-spotted spider mites.

habitat, miticide applications, and supplying adequate irrigation to avoid dry plant material that encourages mite infestation (James and Barbour, 2009). Miticides are not always completely effective, and biological controls play an important role in mite control (James and Castle, 2005). Organic growers use overhead misting to cool the hopyard and prevent the hot, dry, dusty conditions that exacerbate mite problems (James and Barbour, 2009; Opit et al., 2006). The use of pheromones to control the California prionus beetle (*Prionus californicus* Motschulsky) in hopyards has been effective, and such tactics could carry over to organic systems (Maki et al., 2011). The organically certified chemical controls against arthropod pests in organic crop production are limited and generally less stable and effective than their synthetic counterparts due to uncertain efficacy, potential harm to beneficial arthropods, and cost. Insecticidal sprays should be used when other methods, such as natural resistance, biological controls, and predatory arthropods, have failed (Zehnder et al., 2007).

Quantity and diversity of arthropods increase with the use of cover crops as compared to exposed soils, whereas they decrease with the use of chemicals, soil exposure, tillage, and cultivation (Fernández et al., 2008). A comprehensive study by Grasswitz and James (2009) focused on responses of beneficial predator insects on hop plants (‘Cascade’) in Washington State with a cover crop of flowering annuals. Their findings indicated an overall increase in several beneficial arthropods due to the presence of cover crops; the majority of insects resided in the understory, however, and had little effect on some pest populations on the hop canopy itself. The largest effect of cover-cropping on pest species was on spider mites, although the cause is unclear—whether it be reduced dust, increased humidity, or other changes in microclimate (Grasswitz and James, 2009). In addition, development of insect-resistant varieties is seen as a possibility. Paul (1996) documented strong field resistance of hops to damson-hop aphid. The most common beneficial arthropods in hopyards include several species of predatory mites (*Galendromus occidentalis, Neoseiulus fallacies,* and *antystis* ssp.); predatory lady beetles; predatory bugs that include *Orius tristicolor*, *Geocoris pallens*, and *Deraeocoris brevis*; as well as assassin bugs (*Reduviidae*), parasitic wasps (parasitoids); spiders; and other predatory arthropods (James and Dreves, 2009).

Other notable hop pests include: the California prionus beetle; the garden symphylan (*Scutigerella immaculate*, Newport); the hop flea–beetle, which is represented by two different species—(*Psylliodes punctulatus* Melsheimer) in North America and (*P. attenuatus,* Koch [Coleoptera: Chrysomelidae]) in the Palaearctic ecozone; and the hop looper (*Hypena humuli*, Harris), among other Lepidoptera. Of these Lepidoptera, the hop looper is becoming an increasingly important pest in North America. Numerous species of root weevil (*Otiorhynchus* [Coleoptera: Curculionidae]), the rosy rustic moth (*Hydraecia micacea*, Esper), and the cyst nematode (*Heterodera humuli*, Filipjev) are also pests of the hop plant (Grasswitz and James, 2008; Mahaffee et al., 2009a).

Conventionally grown raw hops have relatively high levels of pesticide residues (Hengel and Shibamoto, 2002). Pesticide residue levels were tested by Hengel and Shibamoto (2002) throughout the brewing process using hops treated with seven common pesticides in a commercial setting. Tebuconazole, Z-dimethomorph, and E-dimethomorph—all Category 3 fungicides—were the only tested compounds that were present in the wort (unfermented beer) at detectable levels: 0.001, 0.008, and 0.005 ppm respectively (Hengel and Shibamoto, 2002; Walsh, 2009). The amount of tebuconazole present after 38 d of fermentation had dropped below the limit of quantification of 0.0005 ppm, while levels of Z-dimethomorph and E-dimethomorph had not reduced from the levels present before fermentation (Hengel and Shibamoto, 2002). According to the previous study, the pesticides tested were greatly reduced through the brewing process; however, all compounds have not been tested, and residues on some of the compounds were found in the final product. Even these relatively small amounts of pesticide residue may concern organic consumers, as recent evidence shows that even low levels of certain pesticides and combinations thereof can have detrimental health effects (Kuter et al., 2010; Lotter, 2003; Merhi et al., 2010; Yavuz et al., 2010).

Irrigation

Hops require copious amounts of irrigation in most commercial fields to optimize yield and quality, but the quantity of irrigation is dependent on local climate. Application of approximately 700 to 800 mm of irrigation water throughout the growing season is typical in arid climates, but timing and need can vary greatly between locations. In arid regions, irrigation is generally required from mid-spring until shortly before harvest (Beatson et al., 2009). Drip systems offer the most efficient means of irrigation and are increasing in popularity. Though the initial cost of drip irrigation is high, its efficiency and ability to fine-tune nutrient delivery through a single system is helpful in managing conventionally grown hop crops (Wright and Cone, 1999). Furrow, overhead sprinkler, and hand-moved sprinkler irrigation methods are still used in some hopyards, and the use of non-drip irrigation is often necessary to establish cover crops (Beatson et al., 2009).

Cover crop use in hopyards is limited by climate and method of irrigation. Organic hop systems that rely on cover crops may require a different approach to irrigation in some regions. The establishment of beneficial cover crops likely will require overhead irrigation in drier climates, which will increase humidity and cool the hopyard. This may cause increased problems with downy mildew but likely will decrease the impact of spider mites, as they prefer hotter, drier temperatures (Mahaffee et al., 2009a; Opit et al., 2006). The inefficiency of overhead irrigation will have to be assessed, and the impact of increased water use will vary depending on location and availability of water. Environmental benefits of cover crops may be countered by some degree to the increase in water usage and inefficiency of overhead irrigation. This needs further investigation. A combination of irrigation methods may provide the best solution to balance these issues. Cover crop studies in hopyards will be necessary to discover the most advantageous crops to use and most efficient methods of establishment. Different climates likely will require different cover-cropping regimes, necessitating cover crop studies in different production regions.

HOP BREEDING

For Organic Systems

Humulus lupulus is a diploid ($2n = 2x = 20$) with a basic chromosome number of 10 (Beatson et al., 2003). Tetraploid ($2n = 4x = 40$) hop lines have been established through colchicine (an antimitotic agent) mediated techniques and the use of sexually derived tetraploids (Beatson et al., 2001; Roy et al., 2001). These tetraploids are then bred with diploid plants to produce triploid ($2n = 3x = 30$) plants, which are considered in some cases to be superior in vigor and yield, as well as possessing the desirable characteristic of being generally seedless (Roy et al., 2001). Seeds are undesirable in hops due to increased weight and decreased brewing quality (Henning et al., 2009). Two of the more common triploid hop cultivars are 'Willamette' and 'Mount Hood' (Jakse et al., 2001).

Several of the most important factors to consider when breeding hop varieties are described by Lemmens (1998) and can be divided into two categories: brewing and agronomic qualities. Brewing qualities include aroma, essential oils, soft resins, α acids, β acids, hop storage index, preservative or antiseptic quality, and polyphenols. Henning and Townsend (2005) divide the characteristics into α acid, β acid, cohumulone, colupulone, xanthohumol concentrations, and yield. They note that increases in some characteristics will simultaneously result in increases of others. A study by De Keukeleire et al. (2007) compared α and β acid production over 3 yr in three hop varieties grown under organic and conventional production methods ('First Gold', 'Admiral', and 'Wye Challenger'). The results showed a slight trend toward an increase in key α and β acid compounds during all 3 yr in the organically produced First Gold, but the other varieties tested exhibited no clear tendency. However, the trend was not statistically significant because, by the time of harvest, the difference in acid had dropped to levels below those of statistical significance. This study does suggest that different cultivars can exhibit different patterns of growth and acid levels under organic production. It also suggests that some hop varieties may perform better than others in organic growing conditions, and that responses in secondary metabolite production seem to be a function of stress to the plant (De Keukeleire et al., 2007). The possibilities of some cultivars performing better under organic conditions and producing a better acid profile are worth further investigation, and there is a need for similar studies of organic variety trials using more cultivars over a longer period of time.

Hop breeding has traditionally focused on the female plant, with the male plant used as a source of offspring for selection and not as a unique source of genetic variation. Recent analysis of the genetics of male samples has enabled utilization of the variability present in male plants (Henning and Townsend, 2005). Traditionally, European plants of the *lupulus* variety have been the primary source of genetic material for hop breeding, while the earliest cultivars were likely the result of landrace selection (Peredo et al., 2009; Townsend and Henning, 2009). Wild American varieties (*neomexicanus*, *pubescens*, and *lupuloides*) have been, and are currently, used in breeding efforts to produce different characteristics and resistances. Although Asian varieties *fengxianensis* and *cordifolus* have not been widely used in breeding efforts, it is expected that resistances and favorable characteristics will be found in wild samples and used in breeding efforts as well (Peredo et al., 2009). Unique sources of wild germplasm are of high value to future hop breeding and production, providing traits such as disease and pest resistance, frost and drought tolerance, dwarf growth habits, improved yield, and diverse chemical profiles, all of which should prove advantageous to organic breeding and sustainable hop production efforts (Hampton et al., 2001).

Agronomic qualities that are important to growers and can be manipulated by breeding efforts include disease resistance, pest resistance, cone structure, cone color, yield, ripening date, twining habit, bine length, and drying habits (Lemmens, 1998). In organic hopyards, disease- and pest-resistance, nutrient-use efficiency, and brewing quality will be growers' chief concerns. The lack of inputs of synthetic N fertilizer, fungicide, and pesticide will increase the importance of these traits in organic systems (Lammerts van Bueren et al., 1999). Selection protocol for conventional breeding systems needs to be modified to meet the needs of organic and low-input systems. Traits that are desirable in conventional systems may not be advantageous in these low-input systems. Organic-specific breeding efforts and their subsequent varieties should be developed to optimize positive traits needed in an organic farming system (Murphy et al., 2007).

Low-Trellis Systems and Dwarfing Varieties

Low-trellis systems and the breeding and use of dwarf hop varieties may prove highly conducive to organic farming practices and may represent a unique opportunity for organic hop growers. Dwarf varieties have shorter internodes and smaller leaves than traditional tall- or high-trellis hops. They are grown on low-trellis systems 2.3 to 3 m in height compared with the traditional 5.5-m trellis. They are relatively untrained, which allows the plants to grow in a continuous, dense hedgelike form in which the bines are not removed during harvest but allowed to senesce. Harvested material is then cleaned to remove the leaves, stems, and other plant debris (Beatson et al., 2009; Darby, 2005). Growers are especially interested in dwarf hop varieties grown on low-trellis systems, with nearly 24% of the UK's hop hectarage devoted to dwarf hops in 2005 (Darby, 2007). Most traditional hop varieties cannot be successfully grown on low-trellis systems because of an associated 40 to 60% yield reduction (Seigner et al., 2008). A major advantage of dwarf hops and the low-trellis system is the potential reduction in labor costs compared with traditional high-trellis systems. On-site mechanical harvesting and potential for reduced labor involved with seasonal training may help make dwarf hops a viable option for small-scale organic growers to exploit. Low-trellis systems also offer ecological benefits, as they can be sprayed more efficiently and with less spray-drift due to the close proximity of plant material and lower stature (Darby, 2005).

Dwarf varieties also have advantages in attracting an abundance of beneficial predatory insects on the hop plants. This is because of the increase in plant material near the soil, the close proximity of adjacent hop foliage and cover crop habitats, and the changes in the microclimate of the hopyard, all of which result in cooler more moist conditions (Darby, 2004). Beneficial insects tend to be located near the ground. This suggests that, in low-trellis systems, beneficial insects would be in higher concentrations on more of the hop plant when compared with traditional high-trellis hops where the insects are unlikely to travel high up the plant. Biological mite control is likely to be more viable in dwarf hopyards (Darby, 2004; Lilley et al., 1999). The plant material typically left behind after harvest may lead to increased habitat for mites compared with traditional hopyards, where spent material is removed from the field at harvest (Lilley et al., 1999).

Current dwarf hop varieties are primarily the low-α aroma hops, with the exception of 'Summit', a high-α semi-dwarf variety that was released in Prosser, WA (Darby, 2007; Jeske, 2007). Summit is not a true dwarf but still is better-suited to low-trellis systems than most traditional hop varieties (Jeske, 2007). Dwarf hops are considered by some to be inferior to traditional hops in regard to brewing quality due to their low-α acid concentrations (Seigner et al., 2008). Existing English dwarf varieties also exhibit susceptibility to mildews (Seigner, 2008). Breeding efforts are under way to increase α acid levels while retaining or increasing disease- and pest-resistance, as well as the beneficial dwarf growth habit. High-α varieties of dwarf hops are not expected to be widely available until 2020–2025. Another goal of dwarf hop breeding programs is developing high-β acid varieties for use in the pharmaceutical-medical industry (Seigner et al., 2008).

Low-trellis systems and the breeding and use of dwarf hop varieties may prove highly conducive to organic farming practices and represent a unique opportunity for organic hop growers. Although they will likely never replace high-trellis varieties, the option of dwarf hops may increase farmers' ability to better match their growing conditions and goals to their crop and allow them to remain more competitive while doing so. Dwarf hop varieties likely will continue to develop in coming years, and their use may prove important to future organic hop production efforts. The potential ecological benefits of dwarf and low-trellis hop production make it an ideal candidate for organic trials. Research is needed to determine if the reduced labor costs and potential ecological benefits outweigh the reduced yields, considering the price premiums associated with an organic crop.

ALTERNATIVE USES FOR HOPS

Ninety-eight percent of hops grown globally were used for the purposes of brewing beer in 1990, while 3 to 5% of the world's hop crop was used in sugar processing and as a preservative in ethanol production (Carter et al., 2000; Mahaffee and Pethybridge, 2009). Although the primary use of the hop plant is for brewing purposes, recent research shows promising possibilities for other uses of the hop plant and its extracts. Hops recently have been approved by the European Scientific Cooperative on Phytotherapy for use in treating excitability, mood disturbances, and sleep disturbances (Zanoli and Zavatti, 2008). Xanthohumol, isoxanthohumol, and other prenylflavonoids present in hop cones may prove beneficial in their cancer-fighting abilities (Delmulle et al., 2008; Gerhauser et al., 2002). The flavonoids in hop cones also show promise as an antioxidant and antiviral, especially against HIV (Wang et al., 2004). Gardea-Torresdey et al. (2002) suggest that hop by-products look hopeful in their ability to clean up aqueous lead(II) contamination. Spent bines also can be used as a source of fiber for other functions, including the production of fiberboard (Griffin and Emck, 1982; Hampton et al., 2001).

Use of hop components as an antimicrobial agent in animal feed may further increase demand for the crop (Mahaffee and Pethybridge, 2009). A new, low-α acid cultivar named 'Teamaker' was released by USDA-ARS in 2006. The cultivar lacks bittering acids but retains the β acids, which are primarily responsible for the preservative, medicinal, and antimicrobial properties of hops. In coming years, Teamaker and future low-α, high-β cultivars may be in demand for their antimicrobial characteristics (Henning et al., 2008). Although non-beer use of hops only represents a small fraction of production at this time, discoveries in the last several decades of new uses of the plant, its by-products, and its phytochemicals may further increase the non-brewing use and subsequent demand for the crop.

CONCLUSIONS

The majority of public hop research is focused on the specific chemicals produced by the hop plant and their interactions with living tissue, while agronomic and especially organic hop research lags behind. The availability of organic hop-specific research is extremely limited, and many aspects of basic hop agronomy are lacking as well. Nevertheless, organic hop production and research likely will become more widespread as hops are removed from USDA's organic exemption list, which is likely to increase demand. Organic hop production may need to focus on avoiding large-scale mono-crop systems to help alleviate pest and disease impact.

Establishing reliable methods of pest, disease, and weed control will be key for organic hop growers to be successful, but this may require different strategies depending on environmental and cultural practices. Cover-cropping will be essential to provide beneficial insect habitat and build soil quality and available nutrients. Organic-specific breeding efforts also will be critical to establish cultivars with the positive traits that may put them at an advantage in organic production, such as high nutrient- and water-use efficiencies, strong disease- and pest-resistance, ability to yield well on low-trellis systems, and positive brewing and storage characteristics. Organic production is inherently dependent on the evaluation of environmental influences to develop the cropping system that performs best on a specific site; thus, it will not have a clear-cut set of guidelines. An integrated approach will be necessary to meet all of the needs of an organic hopyard.

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REFERENCES

Abawi, G., and T. Widmer. 2000. Impact of soil health management practices on soilborne pathogens, nematodes, and root disease of vegetable crops. Appl. Soil Ecol. 15:37–47. doi:10.1016/S0929-1393(00)00070-6

American Organic Hop Grower Association (AOHGA). 2011. Organic hop market report (May 2011). Available at http://usorganichops.com/AOHGA/index/Entries/2011/5/31_Organic_Hop_Market_Report_%28May_2011%29.html (verified 1 Aug. 2011). AOHGA, info@usorganichops.com.

Ashford, D.L., and D.W. Reeves. 2003. Use of a mechanical roller-crimper as an alternative kill method for cover crops. Am. J. Altern. Agric. 18:37–45. doi:10.1079/AJAA2003037

Bàrberi, P. 2002. Weed management in organic agriculture: Are we addressing the right issues? Weed Res. 42:177–193. doi:10.1046/j.1365-3180.2002.00277.x

Beatson, R., S. Kenny, S. Pethybridge, and D. Gent. 2009. Hop production. p. 5–8. *In* W. Mahaffee et al. (ed.) Compendium of hop diseases and pests. The American Phytopathological Society, St. Paul, MN.

Beatson, R., A. Ferguson, I. Weir, L. Graham, K. Ansell, and H. Ding. 2001. Identification and use of sexually derived tetraploids in hop (*Humulus lupulus* L.). *In* E. Seigner (ed.) International Hop Growers' Convention, Canterbury, Kent, UK.

Beatson, R., A. Ferguson, I. Weir, L. Graham, K. Ansell, and H. Ding. 2003. Flow cytometric identification of sexually derived polyploids in hop (*Humulus lupulus* L.) and their use in hop breeding. Euphytica 134:189–194. doi:10.1023/B:EUPH.0000003882.23615.c5

Burgess, A. 1964. Hops: Botany, cultivation, and utilization. Interscience Publishers, New York.

Carter, P., E. Oelke, A. Kaminski, C. Hanson, S. Combs, J. Doll, G. Worf, and E. Oplinger. 2007. Alternative field crops manual—hop. Available at http://corn.agronomy.wisc.edu/Crops/Hop.aspx (verified 1 Aug. 2011). University of Wisconsin-Extension/University of Minnesota Plant and Animal Products and the Minnesota Extension Service, Madison, WI/St. Paul, MN.

Darby, H., A. Stone, and R. Dick. 2006. Compost and manure mediated impacts on soilborne pathogens and soil quality. Soil Sci. Soc. Am. J. 70:347–358. doi:10.2136/sssaj2004.0265

Darby, P. 2004. Hop growing in England in the 21st century. J. R. Agric. Soc. Engl. 165.

Darby, P. 2005. The history of hop breeding and development. Brew Hist. 121:94–112.

Darby, P. 2007. The UK hop breeding programme: A new site and new objectives. p. 10–13. *In* E. Seigner (ed.) International Hop Growers' Convention, Scientific Commission, IHGC, Tettnang, Germany.

De Keukeleire, J., I. Janssens, A. Heyerick, G. Ghekiere, J. Cambie, I. Roldán-Ruiz, E. Van Bockstaele, and D. De Keukeleire. 2007. Relevance of organic farming and effect of climatological conditions on the formation of α-acids, β-acids, desmethylxanthohumol, and xanthohumol in hop (*Humulus lupulus* L.). J. Agric. Food Chem. 55:61–66. doi:10.1021/jf061647r

Delmulle, L., T. Vanden Berghe, D. De Keukeleire, and P. Vandenbeele. 2008. Treatment of PC-3 and DU145 prostate cancer cells by prenylflavonoids from hop (*Humulus lupulus* L.) induces a caspase-independent form of cell death. Phytother. Res. 22:197–203. doi:10.1002/ptr.2286

Eastwell, K., and T. Sano. 2009. Hop stunt. *In* W.F. Mahaffee et al. (ed.) Compendium of hop diseases and pests. The American Phytopathological Society, St Paul, MN.

Eastwell, K., S.J. Pethybridge, and C. Wilson. 2009. American hop latent virus, hop latent virus, and hop mosaic virus. *In* W.F. Mahaffee et al. (ed.) Compendium of hop diseases and pests. The American Phytopathological Society, St Paul, MN.

Elstein, D. 2002. Mildew-resistant hops tested by brewing industry. Agric. Res. 50:13.

Food and Agricultural Organization of the United Nations. 2010. Food and agricultural commodities production. FAO Statistics Division, Rome, Italy.

Fernández, D., L. Cichón, E. Sánchez, S. Garrido, and C. Gittins. 2008. Effects of different cover crops on the presence of arthropods in an organic apple (*Malus domestica* Borkh) orchard. J. Sustain. Agric. 32:197–211. doi:10.1080/10440040802170624

Gardea-Torresdey, J., M. Hejazi, K. Tiemann, J. Parsons, M. Duarte-Gardea, and J. Henning. 2002. Use of hop (*Humulus lupulus*) agricultural by-products for the reduction of aqueous lead (II) environmental health hazards. J. Hazard. Mater. 91:95–112. doi:10.1016/S0304-3894(01)00363-6

Gent, D. 2009. Pest management, crop loss, and IPM. p. 1. *In* D. Gent et al. (ed.) Field guide for integrated pest management in hops. Available at http://www.usahops.org/index.cfm?fuseaction=research&pageID=2 (verified 1 Aug. 2011). USDA Agricultural Research Service via Hop Growers of America, Moxee, WA.

Gent, D.H., D. James, L. Wright, D. Brooks, J. Barbour, A. Dreves, G. Fisher, and V. Walton. 2009. Effects of powdery mildew fungicide programs on two-spotted spider mite (Acari: Tetranychidae), hop aphid (Hemiptera: Aphididae), and their natural enemies in hop yards. J. Econ. Entomol. 102:274–286. doi:10.1603/029.102.0137

George, A. 2011. 2010 Statistical Report. Hop Growers of America, Moxee, WA.

Gerhauser, C., A. Alt, E. Heiss, A. Garnal-Eldeen, K. Klimo, J. Knauft, I. Neumann, H.-R. Scherf, N. Frank, H. Bartsch, and H. Becker. 2002. Cancer chemopreventive activity of xanthohumol, a natural product derived from hop. Mol. Cancer Ther. 1:959–969.

Gingrich, C., J. Hart, and N. Christensen. 1994. Hops. *In* Fertilizer guide 79. OSU-Extension Service, Corvallis, OR.

Grasswitz, T., and D. James. 2008. Biology, phenology, and control of *Hypena humuli* (Lepidoptera: Noctuidae), an emerging pest of hops (*Humulus lupulus*) (Cannabaceae) in the USA. Int. J. Pest Manage. 54:333–338. doi:10.1080/09670870802403960

Grasswitz, T., and D. James. 2009. Influence of hop yard ground flora on invertebrate pests of hops and their natural enemies. J. Appl. Entomol. 133:210–221. doi:10.1111/j.1439-0418.2008.01336.x

Griffin, G., and A. Emck. 1982. Utilization of fibrous waste, U.S. Patent 4354879 application. p. 1–3. U.S. Patents and Trademark Office, Alexandria, VA.

Hampton, R., E. Small, and A. Haunold. 2001. Habitat variability of *Humulus lupulus* var. *lupuloides* in upper midwestern North America: A critical source of American hop germplasm. J. Torrey Bot. Soc. 128:35–46. doi:10.2307/3088658

Hartwig, N., and H. Ammon. 2002. Cover crops and living mulches. Weed Sci. 50:688–699. doi:10.1614/0043-1745(2002)050[0688:AIACCA]2.0.CO;2

Hengel, M., and T. Shibamoto. 2002. Method development and fate determination of pesticide-treated hops and their subsequent usage in the production of beer. J. Agric. Food Chem. 50:3412–3418. doi:10.1021/jf020089n

Henning, J., and M. Townsend. 2005. Field-based estimates of heritability and genetic correlations in hop. Crop Sci. 45:1469–1475. doi:10.2135/cropsci2004.0360

Henning, J., S.J. Pethybridge, and D.H. Gent. 2009. Hop cultivars and breeding. *In* W.F. Mahaffee et al. (ed.) Compendium of hop diseases and pests. The American Phytopathological Society, St Paul, MN.

Henning, J., A. Haunold, M. Townsend, D.H. Gent, and T. Parker. 2008. Registration of 'Teamaker' hop. J. Plant Reg. 2:13–14. doi:10.3198/jpr2007.02.0105crc

Hermanson, R., W. Pan, C. Perillo, R. Stevens, and C. Stockle. 2000. Nitrogen use by crops and the fate of nitrogen in the soil and vadose zone. p. 66–69. *In* Washington State Dep. of Ecology. Washington State University and Washington State Dep. of Ecology, Olympia, WA.

Hord, N.G., Y. Tang, and N.S. Bryan. 2009. Food sources of nitrates and nitrites: The physiologic context for potential health benefits. Am. J. Clin. Nutr. 90:1-10. doi:10.3945/ajcn.2008.27131

Jakše, J., K. Kindlhofer, and B. Javornik. 2001. Assessment of genetic variation and differentiation of hop genotypes by microsatellite and AFLP markers. Genome 44:773–782. doi:10.1139/gen-44-5-773

James, D., and S. Castle. 2005. Conservation biological control and HIPPOs in arthropod pest management in Washington hops. Acta Hortic. 668:167–172.

James, D., and A. Dreves. 2009. Beneficial arthropods. p. 52–68. *In* D. Gent et al. (ed.) Field guide for integrated pest management in hops. Available at https://sharepoint.cahnrs.wsu.edu/hops/Hop IPM Manual/HopPocketGuideFINAL.pdf (verified 12 Aug. 2011). Washington Hop Commission, Moxee, WA.

James, D., and J. Barbour. 2009. Two-spotted spider mite. p. 67–69. *In* W.F. Mahaffee et al. (ed.) Compendium of hop diseases and pests. The American Phytopathological Society, St Paul, MN.

Jeske, R. 2007. U.S. Patent: Hop plant named 'Summit', U.S. Patents and Trademark Office, Alexandria, VA.

Johnson, D., B. Engelhard, and D. Gent. 2009. Downy mildew. p. 18–22. *In* W.F. Mahaffee et al. (ed.) Compendium of hop diseases and pests. The American Phytopathological Society, St Paul, MN.

Keupper, G., K.L. Adam, and P. Williams. 2005. Hops: Organic production. National Sustainable Agriculture Information Service. Available at https://attra.ncat.org/attra-pub/summaries/summary.php?pub=87 (verified 12 Aug. 2011).

Kirby, E., and D. Granatstein. 2010. Oregon certified organic acreage, sales, and livestock 2005–2009 tables. Washington State University Center for Sustaining Agriculture and Natural Resources. Available at http://csanr.wsu.edu/publications/techreports/Organic%20Stats/OR_Organic_Tables_2009.pdf (verified 15 Aug. 2011). Washington State University, Wenatchee, WA

Kirby, E., and D. Granatstein. 2011. Washington State certified organic acreage, sales, and dairy cattle, 2005–2010 tables. *In* Washington State University, Center for Sustaining Agriculture and Natural Resources. Available at http://www.tfrec.wsu.edu/pdfs/P1774.pdf (verified 1 Aug. 2011). Washington State University, Wenatchee, WA.

Kumar, V., D. Brainard, and R. Bellinder. 2009. Effects of spring-sown cover crops on establishment and growth of hairy galinsoga (*Galinsoga ciliata*) and four vegetable crops. J. Hortic. Sci. 44:730–736.

Kuter, K., P. Nowak, K. Golembiowska, and K. Ossowska. 2010. Increased reactive oxygen species production in the brain after repeated low-dose pesticide paraquat exposure in rats. A comparison with peripheral tissues. Neurochem. Res. 35:1121–1130. doi:10.1007/s11064-010-0163-x

Lammerts van Bueren, E., M. Hulscher, M. Haring, J. Jongerden, J. van Mansvelt, A. den Nijs, and G. Ruivenkamp. 1999. Sustainable organic plant breeding. Louis Bolk Institute, the Netherlands.

Lemmens, G. 1998. The breeding and parentage of hop varieties. Brew Dig. 73:16–26. Available at http://www.brewerssupplygroup.com/Hops.html (verified 12 Aug. 2011), Brewers Digest, St. Paul, MN.

Lilley, R., C. Campbell, and M. Ridout. 1999. Vertical dispersal of the two-spotted spider mite *Tetranychus utricae*, and the predatory mite *Phytoseiulus persimilis* on dwarf hops. Agric. For. Entomol. 1:111–117. doi:10.1046/j.1461-9563.1999.00015.x

Lipecki, J., and S. Berbe. 1997. Soil management in perennial crops: Orchards and hop gardens. Soil Tillage Res. 43:169–184. doi:10.1016/S0167-1987(97)00039-1

Lotter, D.W. 2003. Organic agriculture. J. Sustain. Agric. 21:59–128. doi:10.1300/J064v21n04_06

Mahaffee, W., and S. Pethybridge. 2009. The genus *Humulus*. p. 1–5. *In* W.F. Mahaffee et al. (ed.) Compendium of hop diseases and pests. The American Phytopathological Society, St. Paul, MN.

Mahaffee, W.F., S.J. Pethybridge, and D.H. Gent. 2009a. Compendium of hop diseases and pests. The American Phytopathological Society, St. Paul, MN.

Mahaffee, W.F., B. Engelhard, D.H. Gent, and G. Grove. 2009b. Powdery mildew. p. 25–31. *In* W.F. Mahaffee et al. (ed.) Compendium of hop diseases and pests. The American Phytopathological Society, St Paul, MN.

Majer, D., and M. Virant. 2003. Nitrates in hop cones and beer. *In* E. Seigner (ed.) International Hop Growers' Convention, Institute of Hop Research and Brewing, Zalec, Slovenia.

Maki, E.C., J.G. Millar, J. Rodstein, L.M. Hanks, and J.D. Barbour. 2011. Evaluation of mass trapping and mating disruption for managing *Prionus californicus* (Coleoptera: Cerambycidae) in hop production yards. J. Econ. Entomol. 104:933–938. doi:10.1603/EC10454

Merhi, M., C. Demur, C. Racaud-Sultan, J. Bertrand, C. Canlet, F. Blas, Y. Estrada, and L. Gamet-Payrastre. 2010. Gender-linked haemotopoietic and metabolic disturbances induced by a pesticide mixture administered at low dose to mice. Toxicology 267:80–90. doi:10.1016/j.tox.2009.10.024

Mundt, C. 2002. Use of multiline cultivars and cultivar mixtures for disease management. Annu. Rev. Phytopathol. 40:381–410. doi:10.1146/annurev.phyto.40.011402.113723

Murphy, K.M., K.G. Campbell, S.R. Lyon, and S.S. Jones. 2007. Evidence of varietal adaptation to organic farming systems. Field Crops Res. 102:172–177. doi:10.1016/j.fcr.2007.03.011.

National Organic Standards Board. 2010. Response to petition to remove hops (*Humulus lupulus*) from §205.606. Available at www.ams.usda.gov/AMSv1.0/getfile?dDocName=STELPRDC5088024&acct=nosb (verified 12 Aug. 2011). USDA, Washington, DC.

Noble, R., and S.J. Roberts. 2004. Eradication of plant pathogens and nematodes during composting: A review. Plant Pathol. 53:548–568. doi:10.1111/j.0032-0862.2004.01059.x

Opit, G., G. Fitch, D. Margolies, J. Nechols, and K. Williams. 2006. Overhead and drip-tube Irrigation affect two-spotted spider mites and their biological control by a predatory mite on impatiens. HortScience. 41:691–694.

Ovalle, C., A. del Pozo, M. Peoples, and A. Lavín. 2010. Estimating the contribution of nitrogen from legume cover crops to the nitrogen nutrition of grapevines using a 15 N dilution technique. Plant Soil 334:247–259. doi:10.1007/s11104-010-0379

Pang, X., and J. Letey. 2000. Organic farming: Challenge of timing nitrogen availability to crop nitrogen requirements. Soil Sci. Soc. Am. J. 64:247–253. doi:10.2136/sssaj2000.641247x

Parker, R. 2009. Weed management. p. 69–77. *In* D.H. Gent et al. (ed.) Field guide for integrated pest management in hops. Washington Hop Commission, Moxee, WA.

Paul, T.A., P. Darby, C.P. Green, C.J. Hodgson, and J.T. Rossiter. 1996. Electrical penetration graphs of the damson-hop aphid (*Phorodon humuli*) on resistant and susceptible hops (*Humulus lupulus*). Entomol. Exp. Appl. 80:335–342 doi:10.1007/bf00188026.

Peredo, E., M. Revilla, B. Reed, B. Javornik, E. Cires, J. Prieto, and R. Arroyo-García. 2009. The influence of European and American wild germplasm in hop (*Humulus lupulus* L.) cultivars. Genet. Resour. Crop Evol. 57:575–586. doi:10.1007/s10722-009-9495-2

Pethybridge, S., C. Wilson, F. Hay, G. Leggett, and L. Sherriff. 2002. Effect of viruses on agronomic and brewing characteristics of four hop (*Humulus lupulus*) cultivars in Austrailia. Ann. Appl. Biol. 140:97–105. doi:10.1111/j.1744-7348.2002.tb00161.x

Pethybridge, S.J., D. Barbara, C. Wilson, and K. Eastwell. 2009. Hop latent viroid. *In* W.F. Mahaffee et al. (ed.) Compendium of hop diseases and pests. The American Phytopathological Society, St Paul, MN.

Pethybridge, S.J., F. Hay, D. Barbara, K. Eastwell, and C. Wilson. 2008. Viruses and viroids infecting hop: Significance, epidemiology, and management. Plant Dis. 92:324–338. doi:10.1094/PDIS-92-3-0324

Probasco, G. 1997. U.S. Patent: Hop plant named 'H900322–4'. U.S. Patents and Trademark Office, Alexandria, VA.

Radišek, S. 2009. Verticillium wilt. p. 33–36. *In* W.F. Mahaffee et al. (ed.) Compendium of hop diseases and pests. The American Phytopathological Society, St Paul, MN.

Ramos, M., E. Benítez, P. García, and A. Robles. 2010. Cover crops under different managements vs. frequent tillage in semiarid conditions: Effects on soil quality. Appl. Soil Ecol. 44:6–14. doi:10.1016/j.apsoil.2009.08.005

Roy, A. T., G. Leggett, and A. Koutoulis. 2001. In vitro tetraploid induction and generation of tetraploids from mixoploids in hop (*Humulus lupulus* L.). Plant Cell Rep. 20:489–495. doi:10.1007/s002990100364

Sanguankeo, P., R. Leon, and J. Malone. 2009. Impact of weed management practices on grapevine yield components. Weed Sci. 57:103–107. doi:10.1614/WS-08-100.1

Seigner, E. 2008. Breeding research on hops. p. 30–37. *In* H.D. Institute for Crop Science and Plant Breeding. Annual report 2007—Special Crop Hops, Bayerische Landesanstalt für Landwirtschaft (Bavarian State Research Center for Agriculture), Freising, Germany.

Seigner, E., A. Lutz, H. Radic-Miehle, and S. Seefelder. 2005. Breeding for powdery mildew resistance in Hop (*Humulus l.*): Strategies at the Hop Research Center, Huell, Germany. Acta Hortic. 668:19–27.

Seigner, E., A. Lutz, K. Oberhollenzer, R. Seidenberger, S. Seefelder, and F. Felsenstein. 2008. Breeding of hop varieties for the future. Second International Humulus Symposium, Ghent, Belgium. ISHS Acta Horticulturae 848:49–58.

Sirrine, J., D. Letourneau, C. Shennan, D. Sirrine, R. Fouch, L. Jackson, and A. Mages. 2008. Impacts of groundcover management systems on yield, leaf nutrients, weeds, and arthropods of tart cherry in Michigan. Agric. Ecosyst. Environ. 125:239–245. doi:10.1016/j.agee.2008.01.005

Small, E. 1978. A numerical and nomenclatural analysis of morpho-geographic taxa of *Humulus*. Syst. Bot. 3:37–76. doi:10.2307/2418532

Steenwerth, K., and K. Belina. 2008. Cover crops and cultivation: Impacts on soil N dynamics and microbiological function in a Mediterranean vineyard agroecosystem. Appl. Soil Ecol. 40:370–380. doi:10.1016/j.apsoil.2008.06.004

Steiner, S. 1973. Steiner's guide to American hops. Hopsteiner, New York.

Steinmaus, S., C. Elmore, R. Smith, D. Donaldson, E. Weber, J. Roncoroni, and P. Miller. 2008. Mulched cover crops as an alternative to conventional weed management systems in vineyards. Weed Res. 48:273–281. doi:10.1111/j.1365-3180.2008.00626.x

Stone, A., S. Scheurell, and H. Darby. 2004. Suppression of soilborne diseases in field agricultural systems: Organic matter management, cover cropping, and other cultural practices. p. 131–177. *In* F. Magdoff and R. Weil (ed.) Soil organic matter in sustainable agriculture. CRC Press, Boca Raton, FL.

Sullivan, D., J. Hart, and N. Christensen. 1999. Nitrogen uptake and utilization. p. 10. *In* Pacific Northwest Extension. Pacific Northwest Extension, Oregon State University. Available at http://extension.oregonstate.edu/catalog/pdf/pnw/pnw513.pdf (verified 12 Aug. 2011).

Teasdale, J., C. Beste, and W. Potts. 1991. Response of weeds to tillage and cover crop residue. Weed Sci. 39:195–199.

Thorup-Kristensen, K., J. Magid, and L. Jensen. 2003. Catch crops and green manures as biological tools in nitrogen management in temperate zones. Adv. Agron. 79:227–302. doi:10.1016/S0065-2113(02)79005-6

Townsend, M.S., and J.A. Henning. 2009. AFLP discrimination of Native North American and cultivated hop. Crop Sci. 49:600–607. doi:10.2135/cropsci2008.03.0182

USDA. 2007. National List of Allowed and Prohibited Substances. p. 1–16. *In* USDA Agricultural Marketing Program. Available at http://www.ams.usda.gov/AMSv1.0/NOSB (verified 12 Aug. 2011).

USDA. 2010. US hop statistics. USDA–National Agricultural Statistics Service. Available at http://www.nass.usda.gov/ (verified 12 Aug. 2011).

Walsh, D. 2009. Pesticide toxicity ratings. p. 4–5. *In* D. Gent et al. (ed.) Field guide for integrated pest management in hops. Washington Hop Commission, Moxee, WA.

Wang, Q., Z.-H. Ding, J.-K. Liu, and Y.-T. Zheng. 2004. Xanthohumol, a novel anti-HIV-1 agent purified from hops *Humulus lupulus*. Antiviral Res. 64:189–194.

Watson, C.A., D. Atkinson, P. Gosling, L. Jackson, and F. Rayns. 2002. Managing soil fertility in organic farming systems. Soil Use Manage. 18:239–247. doi:10.1079/SUM2002131

Weihrauch, F. 2009. Damson-hop aphid. p. 60–62. *In* W.F. Mahaffee et al. (ed.) Compendium of hop diseases and pests. The American Phytopathological Society, St Paul, MN.

Wright, L., and W. Cone. 1999. Carryover of imidacloprid and disulfoton in subsurface drip-irrigated hop. J. Agric. Urban Entomol. 16:59–64. Available at http://scentsoc.org/Volumes/JAUE/v16/59.pdf (verified 12 Aug. 2011).

Yavuz, O., A. Aksoy, Y. Kursad Das, M. Yavuz Gulbahar, G. Fatma Yarim, M. Cenesiz, E. Atmaca, and D. Guvenc. 2010. Repeated-dose 14-day dermal toxicity of different combinations of some synthetic pyrethroid insecticides, piperonyl butoxide, and tetramethrin in rats. Cutan. Ocul. Toxicol. 29:16–25. doi:10.3109/15569520903415076

Zanoli, P., and M. Zavatti. 2008. Pharmacognostic and pharmacological profile of *Humulus lupulus* L. J. Ethnopharmacol. 116:383–396. doi:10.1016/j.jep.2008.01.011

Zehnder, G., G.M. Gurr, S. Kühne, M.R. Wade, S.D. Wratten, and E. Wyss. 2007. Arthropod pest management in organic crops. Annu. Rev. Entomol. 52:57–80. doi:10.1146/annurev.ento.52.110405.091337

Zhu, Y., H. Chen, J. Fan, Y. Wang, Y. Li, J. Chen, J. Fan, S. Yang, L. Hu, H. Leung, T.W. Mew, P.S. Teng, Z. Wang, and C.C. Mundt. 2000. Genetic diversity and disease control in rice. Nature 406:718–722. doi:10.1038/35021046